Future muon sources,
Huddersfield,UK 13 Jan 2015

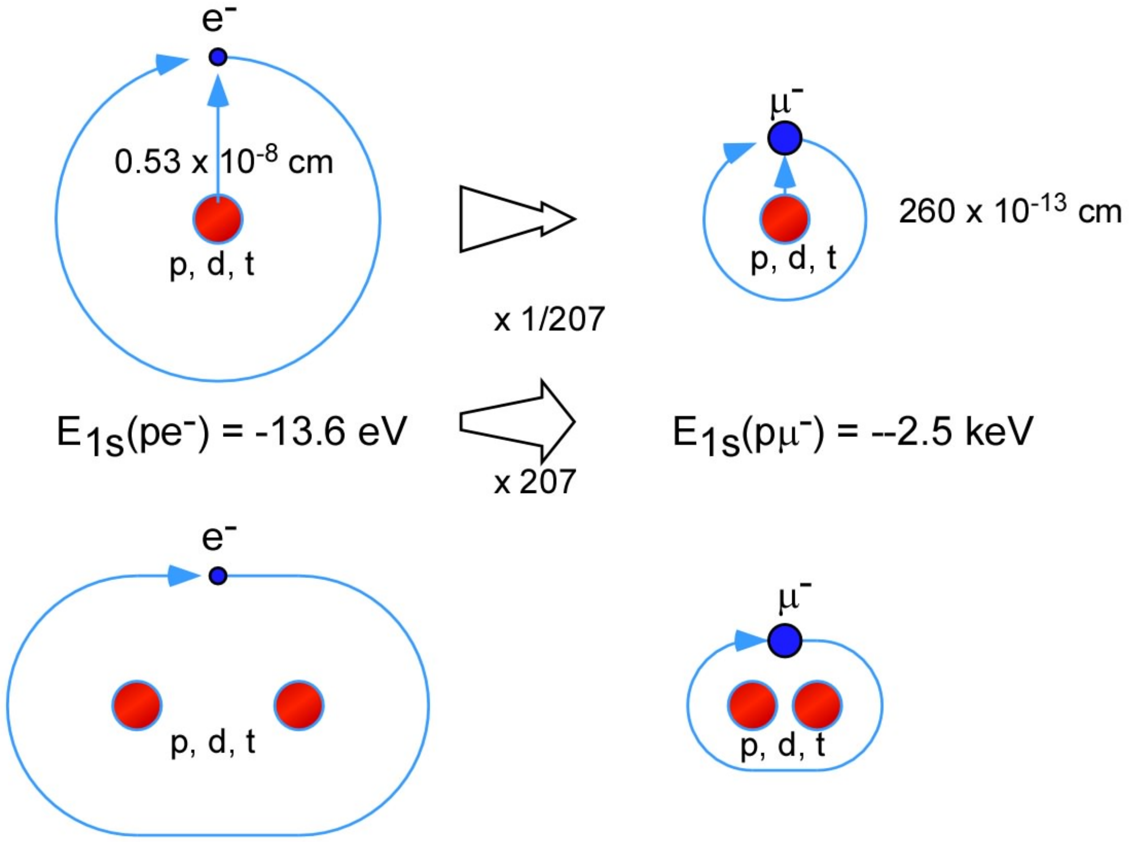
Progress towards muon catalysed fusion (MuCF)

K. Ishida (RIKEN)

MuCF
- Principle
- Facility
- Achievements
- Prospect

μCF Principle

Normal hydrogen atom/molecule vs Muonic atom



$E_{1s}(pe^-) = -13.6$ eV

$E_{1s}(p\mu^-) = --2.5$ keV

$\beta_{g.s.}(ppe^-) = 2\ a_{1s}(pe^-) = 1.1 \times 10^{-8}$ cm

$Eg.s.(ppe^-) = 1/10\ E_{1s}(pe^-) = -1.4$ eV

$\beta_{g.s.}(pp\mu^-) = 520 \times 10^{-13}$ cm

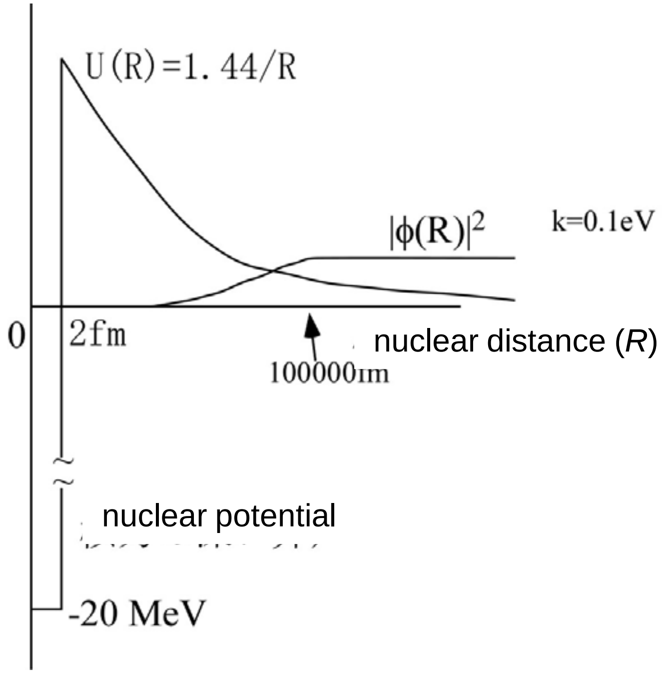
$E_{g.s.}(pp\mu^-) = -250$ eV

μCF Principle

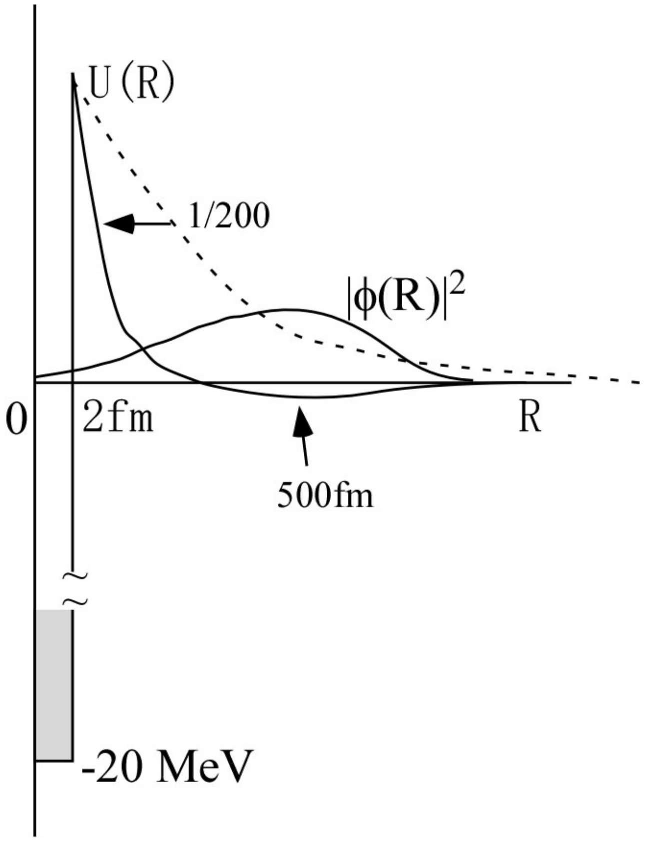
d-t nuclear fusion can be caused by nucleus overlap due to tunneling of Coulomb barrier

Plasma fusion and confinement fusion

increasing translational energy



Muon reduces
Coulomb barrier thickness



μCF Cycle

After injection of muons into D/T mixture

Formation of muonic atoms and molecules

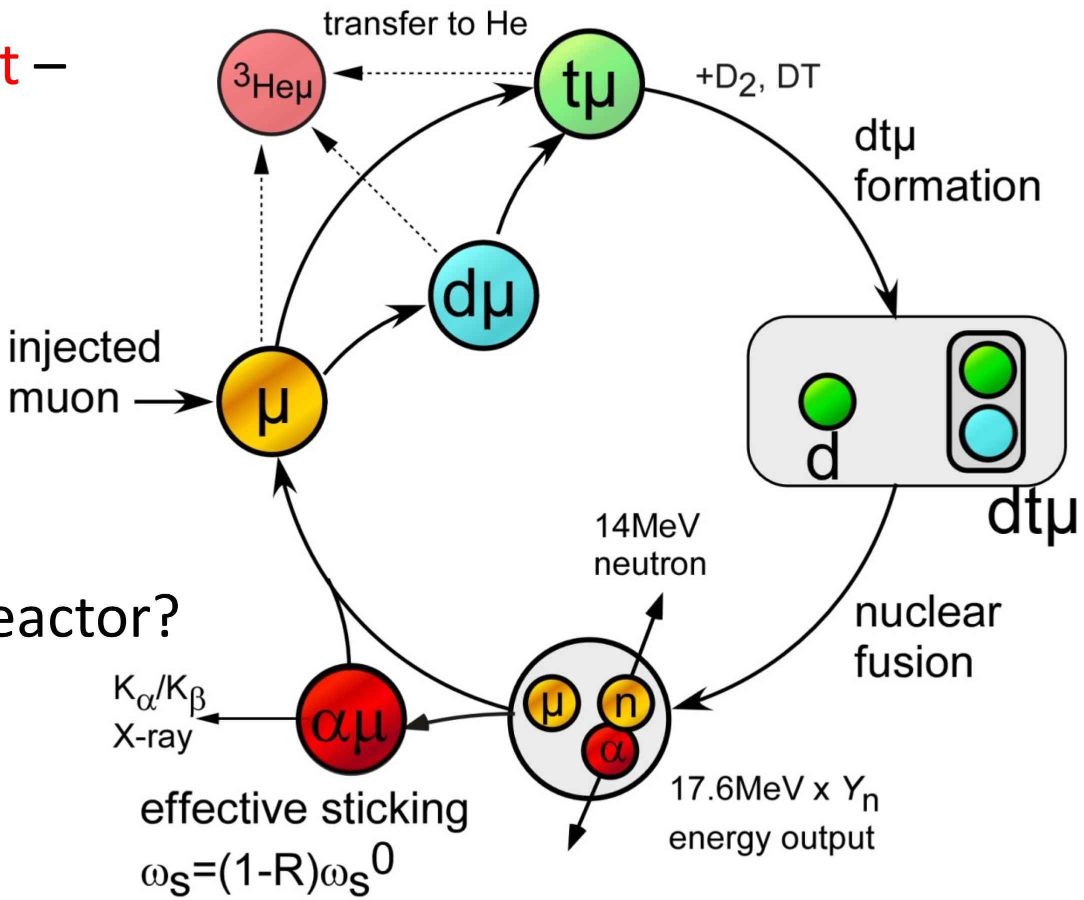
d-t fusion in small dtμ molecule

muon released after d-t fusion

\- muon works as catalyst –

Rich in few body physics.

Can we consider a MuCF reactor?



μCF History

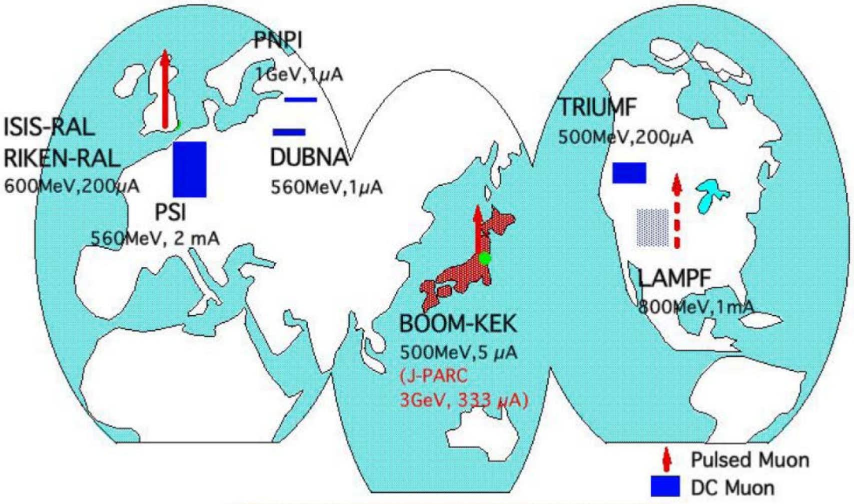
1936 Discovery of muon

1947 Idea of MuCF (F.C. Frank), 1948 (A.D. Sakharov)

1956 First observation of muon induced fusion (Alvarez in bubble chamber)
(1957 Discovery of parity-violation)

1977 Prediction of fast molecular formati

1982- Observation of large dt fusion rate
Studies in Dubna, LNPI, LAMPF, PSI,
TRIUMF and
KEK (1986-)
RIKEN-RAL (1996-)



Muon Sources in the World

μCF in laboratories

Dubna

observation of temperature effect (resonant formation)

LAMPF

First observation of *Y*n>120 high-density D/T

PSI

process in various low density mixtures

αμ ion detection, ...

TRIUMF

tμ atomic beam

KEK

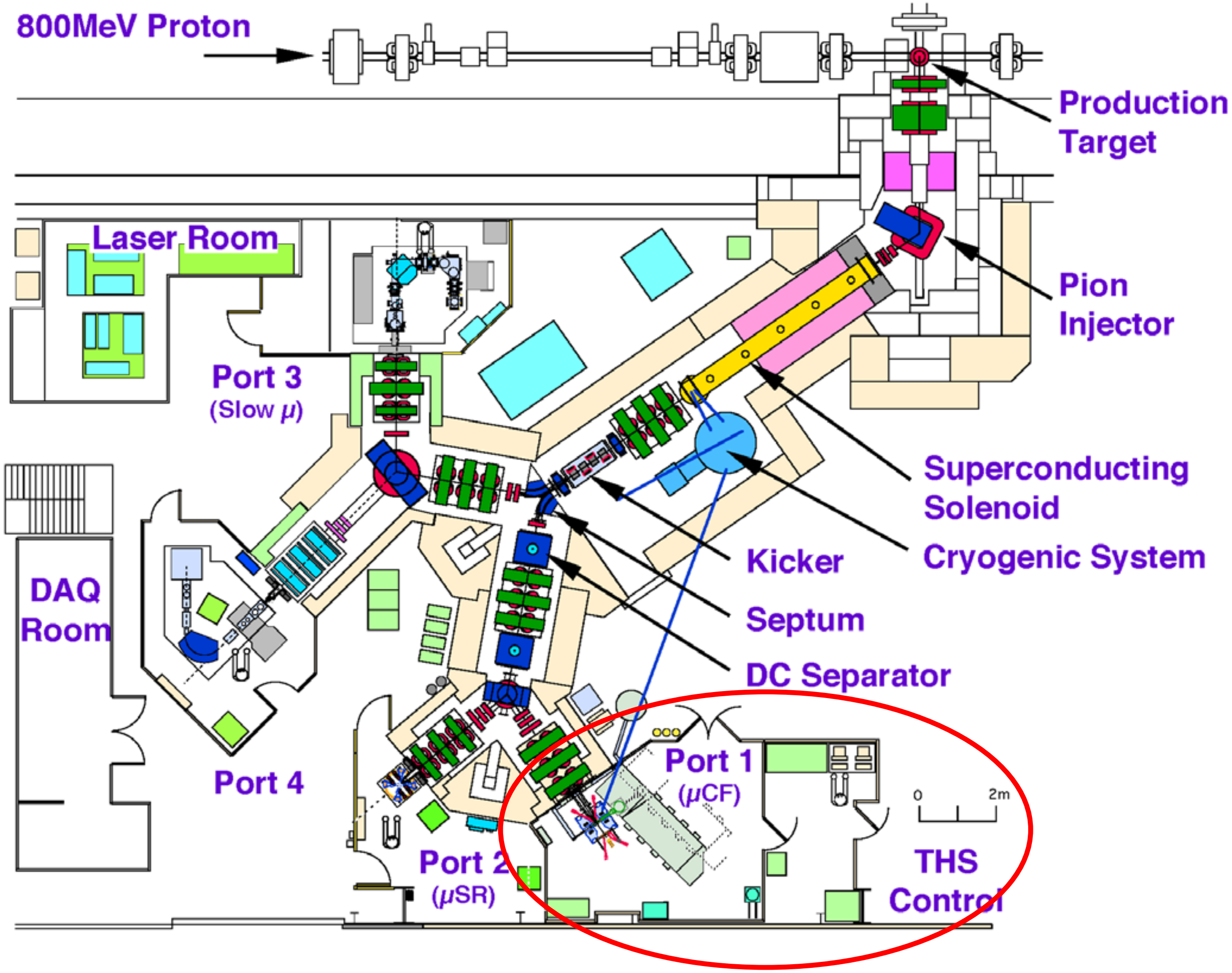
α-sticking x-ray, muon transfer to He

RAL

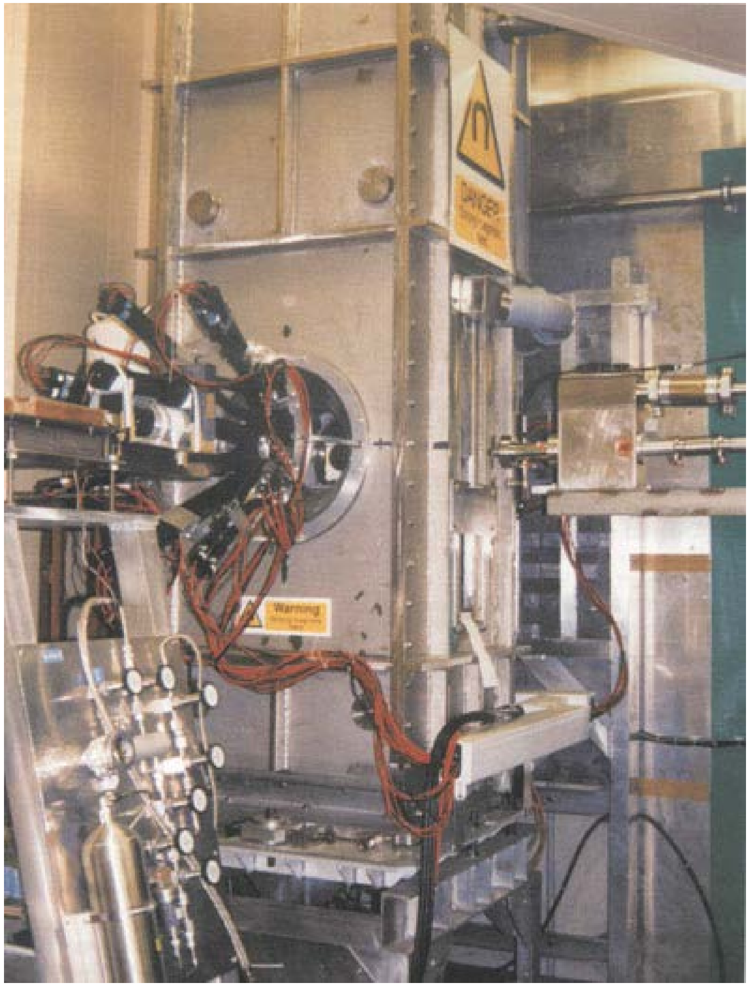
α-sticking x-ray ,

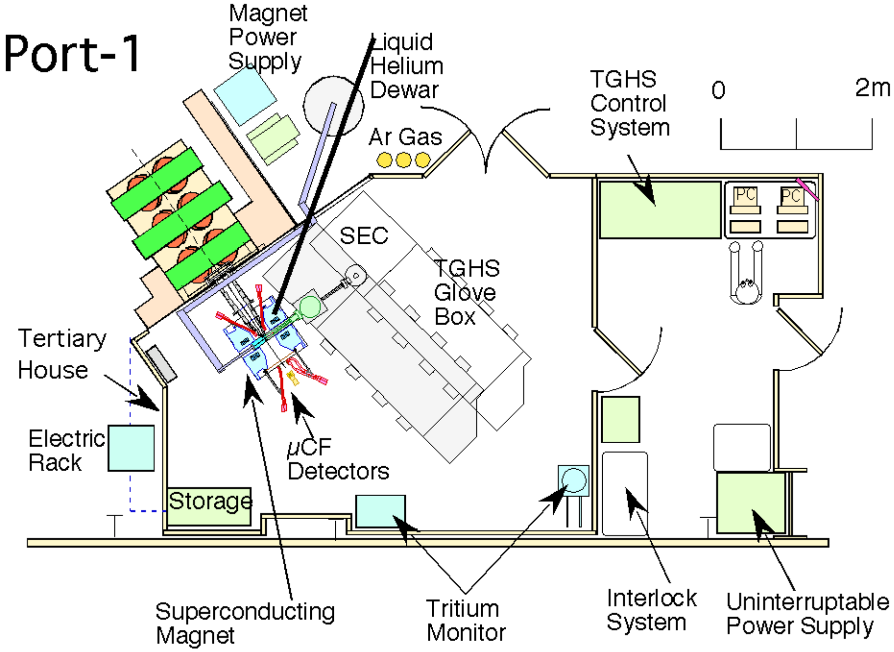
fusion in various mixtures, ...

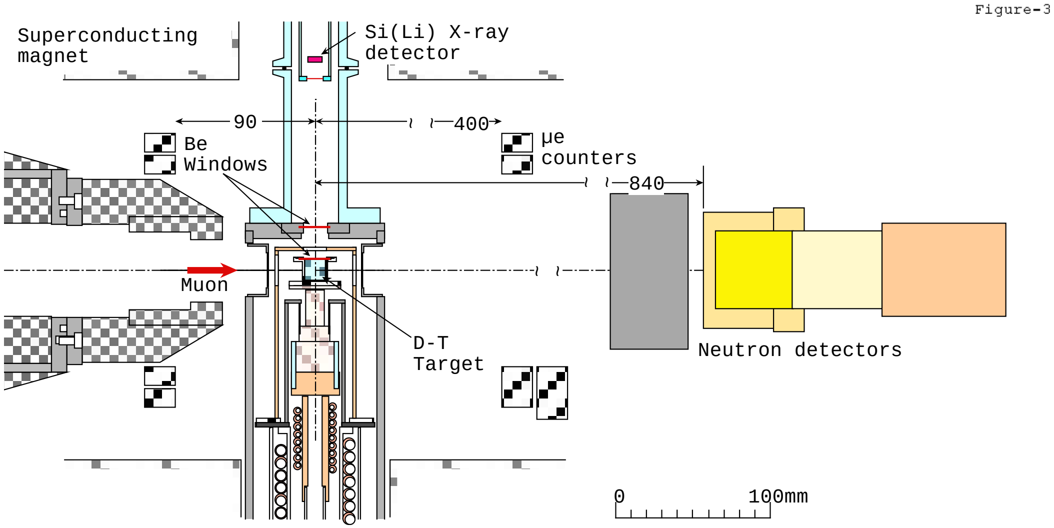
μCF at RIKEN-RAL



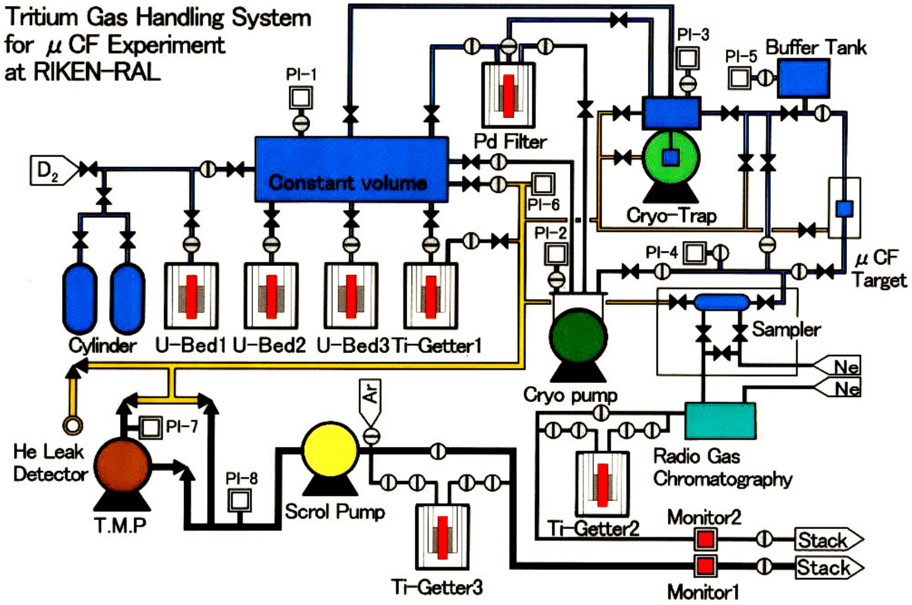
Dedicated μCF facility with safe tritium handling





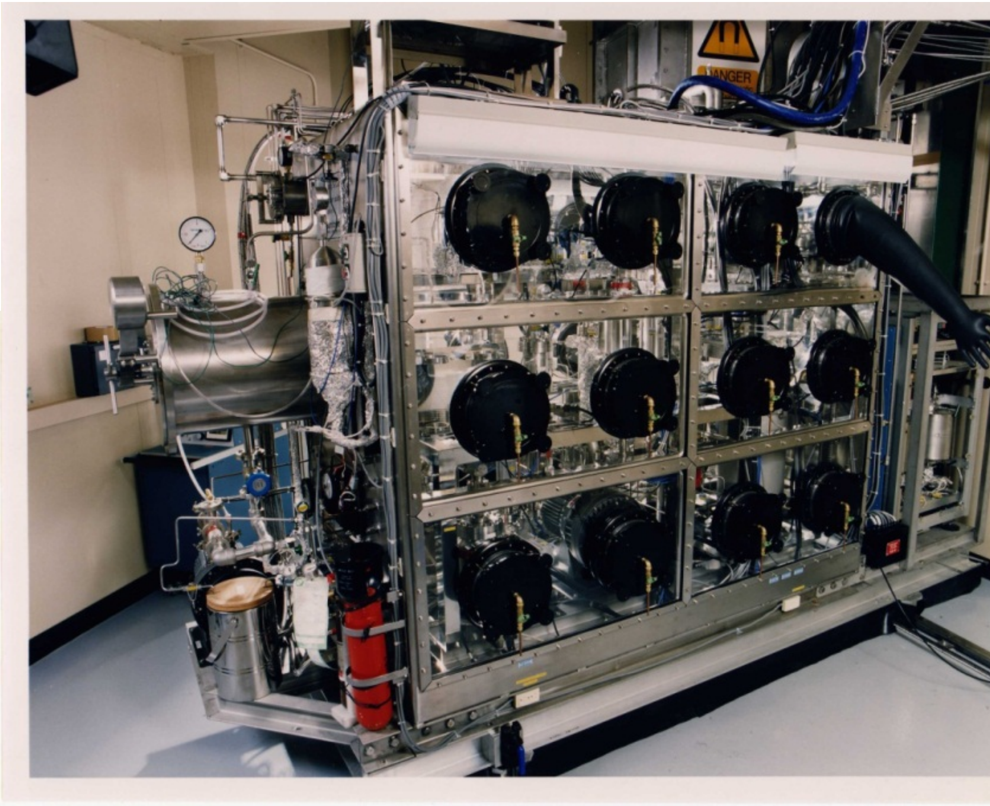


Dedicated facility for tritium safety



Three layers confinement

1. Container and piping
2. Glove box
3. Housing.



Tritium Gas handling System

Purpose:

To supply a high purity D-T target gas (free from ^{3}He component)
for the muon catalyzed d-t and t-t fusion experiments.

Performance:

Purification of the D-T target gas (Pd filter + Cryo-trap)
Adjustment of the D-T mixing ratio
Measurement of the hydrogen isotope components

Handling gas quantity:

D-T gas with the volume of 1.1 liter
The maximum gas pressure of 760 torr
(Handling the D-T gas with negative pressure.)
The maximum tritium gas inventory of 56 TBq (1500 Ci)

Maximizing μCF efficiency

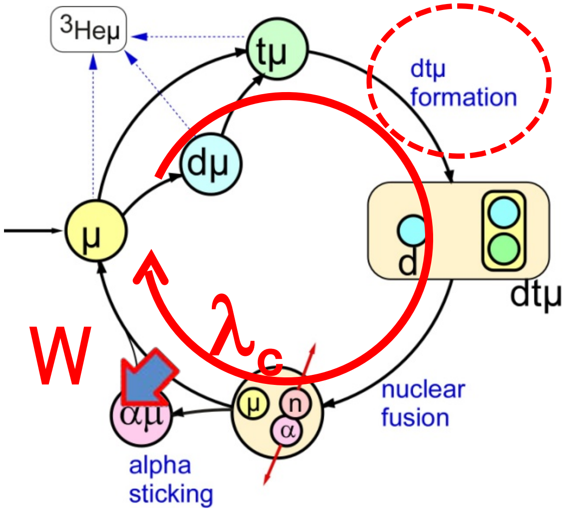
To increasing muCF rate

Cycling rate λ_c (↑) (vs λ_0: muon life)

dtμ formation : tμ + D_2 →[(dtμ)dee]

Muon loss per cycle W (↓)

muon sticking to α-particle, etc

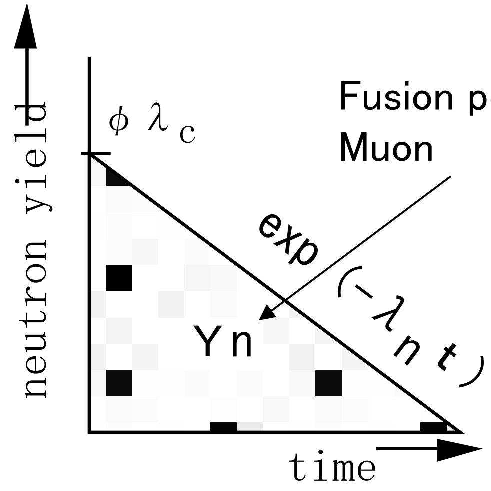


Fusion neutron disappearance rate :

$$\lambda_n = \lambda_0 + W\phi\lambda_c$$

Number of fusion per muon:

$$Yn = \phi\lambda_c/\lambda_n = 1 / [(\lambda_0/\phi\lambda_c)+W]\ (\uparrow)$$



DT target conditions matter:
Temperature, pressure, density, solid,
molecular state etc

Muon production cost

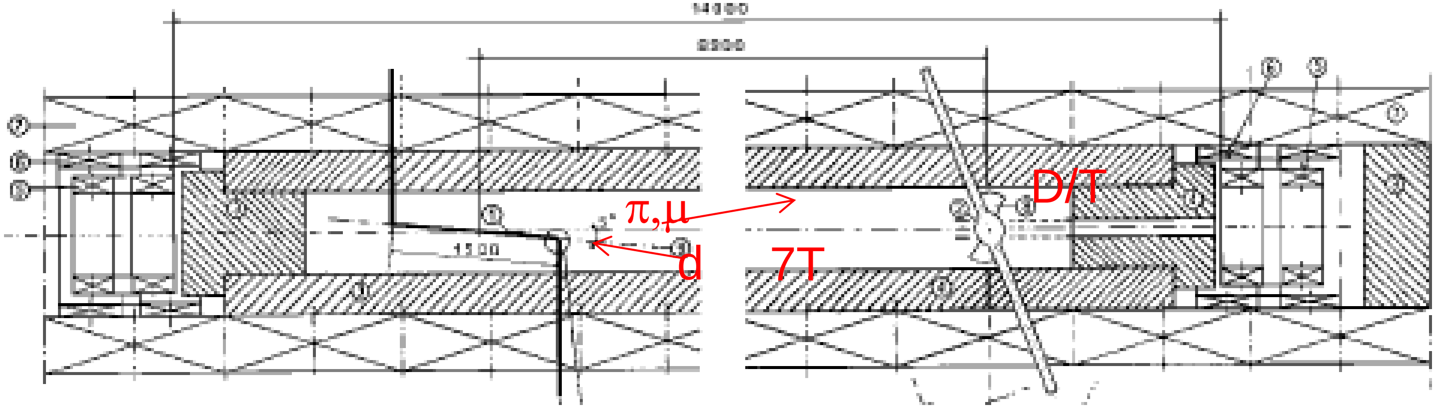
Simulation studies by several groups :

5 Gev beam energy to produce one muon

utilizing large muon confinement solenoid

(needs 300 fusions for energy breakeven)

π^- energy 140 MeV, but
π^+, π^0 and other channels
Δ resonance adds ~150 NeV
kinetic energy to pions



Idea by Y. Mori : Energy recovery FFAG

Could 1 GeV/muon be achieved?

Key process of μCF(1) - dtμ formation

Making bound state

by removing surplus energy (is not so easy)

Auger process

$t\mu + D_2 \rightarrow (dt\mu) + D + e^-$

dissociate molecule by removal of electron

too slow for fusion (2×10^{-6} s)

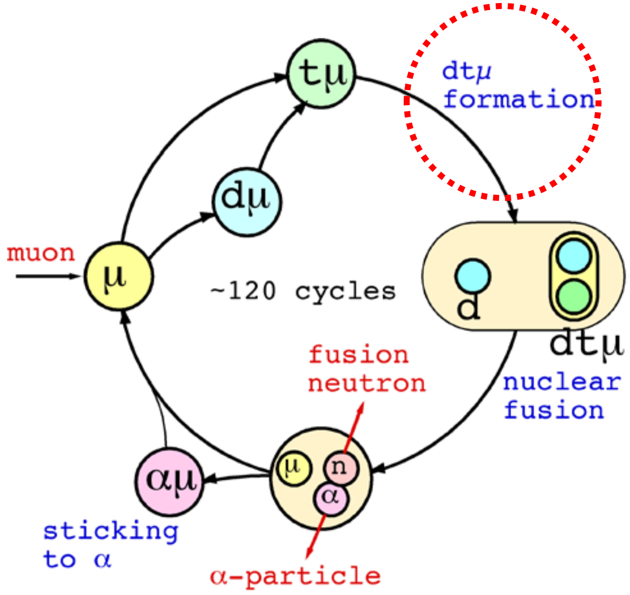
Observation of unexpected fast and temperature dependent rate at Dubna (1975)

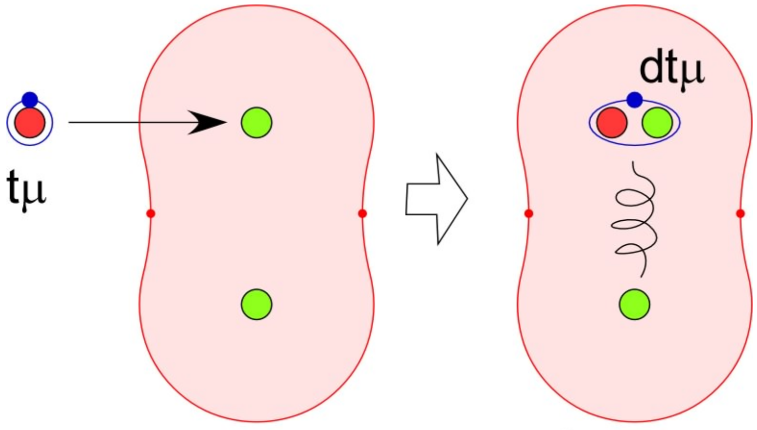
Resonant formation was proposed

Presence of shallow bound state in ddμ、dtμ

$t\mu + D_2 \rightarrow [(dt\mu)Dee]$

Even a small energy difference matters (temperature, molecular state)



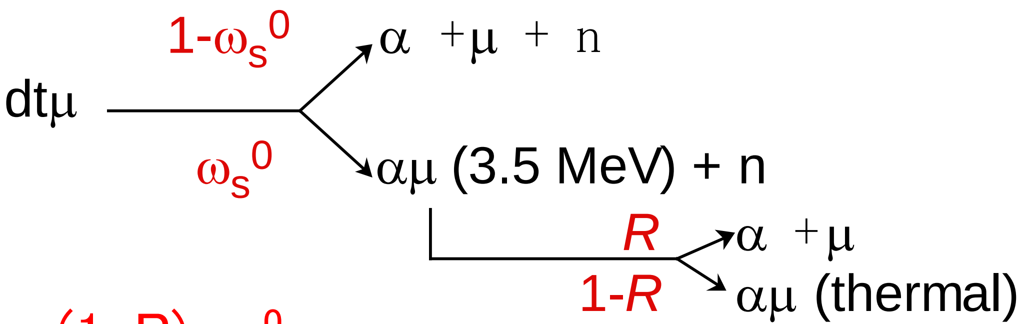


D2 molecule

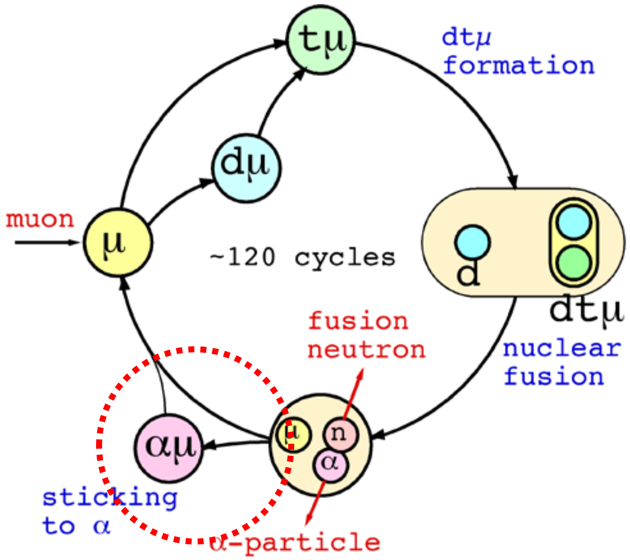
Composite Molecule

Key processes of μCF (2)
μ-to-α sticking

Some of the muons may follow the recoiling a–particle after dt-fusion with small but non-negligible probability ω_s^0,



$$\begin{tikzcd}
 & \alpha + \mu + n & \\
dt\mu \arrow[ur, "1-\omega_s^0"] \arrow[dr, "\omega_s^0"'] & & \\
 & \alpha\mu\ (3.5\ \text{MeV}) + n \arrow[r, "R"] \arrow[dr, "1-R"'] & \alpha + \mu \\
 & & \alpha\mu\ (\text{thermal})
\end{tikzcd}$$



$\omega_s = (1-R)\ \omega_s^0$

ω_s^0 is an intrinsic value determined only by local atomic parameter

$$\omega_s^0\ (nl) = \sum |F(nlm)|^2,\quad F(nlm) = \int \phi_{nlm}(r)\, e^{-iqr}\, \psi_{in}(r)\, dr$$

with powerful few body calculations $\omega_s^0 = 0.9\%$

R (~0.3) can be dependent on target condition

ω_s place limit on the number of fusions

Observation of a-sticking x-rays

$Y_{K\alpha}$ and $Y_{K\beta}$ was measured with good precision for the first time

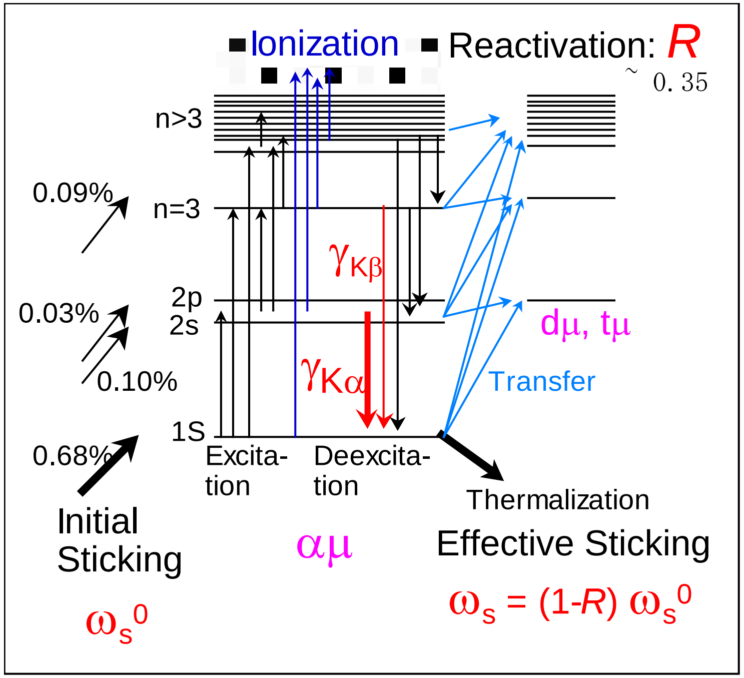
$Y_{K\alpha}$ was consistent with theoretical prediction

$Y_{K\beta}/Y_{K\alpha}$ was much lower than expected

ω_s^0 was slightly smaller

-> less sticking contribution to n$\geq$3 states

(or fast release from n$\geq$3 states)

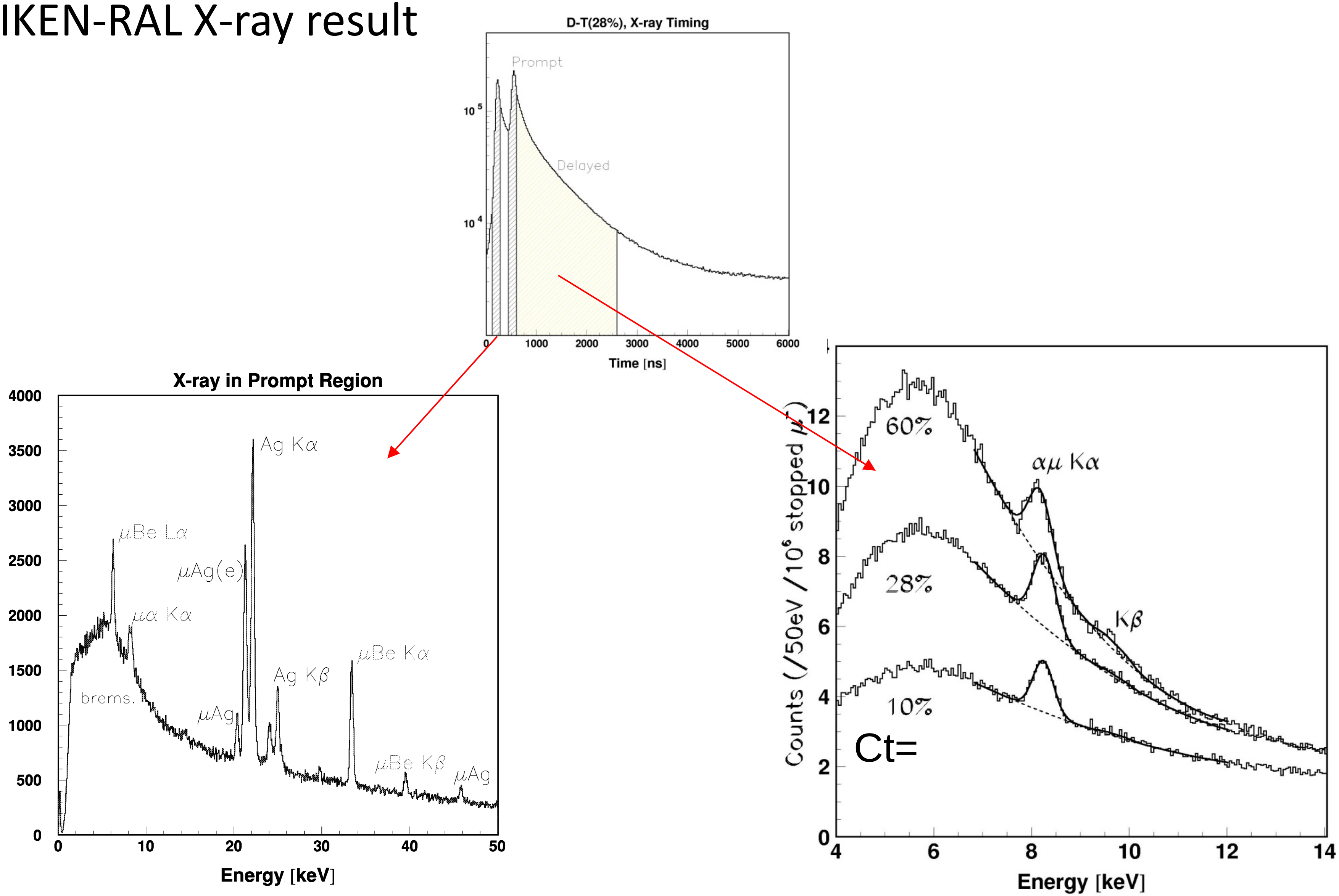


Proof of muon loss process by α-sticking

Had to admit α-sticking still gives severe limit on muCF efficiency

Muon to alpha sticking (RIKEN-RAL X-ray)

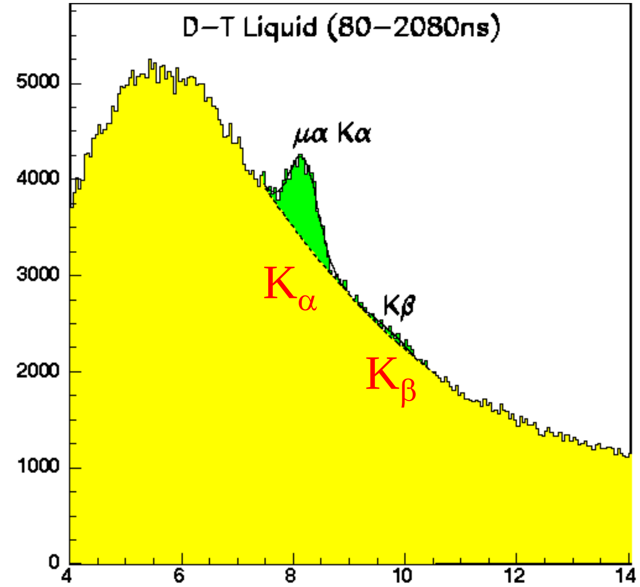
RIKEN-RAL X-ray result

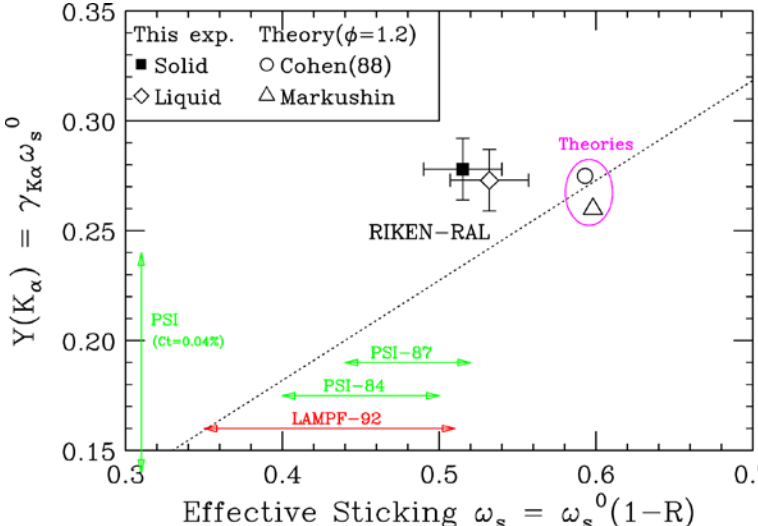


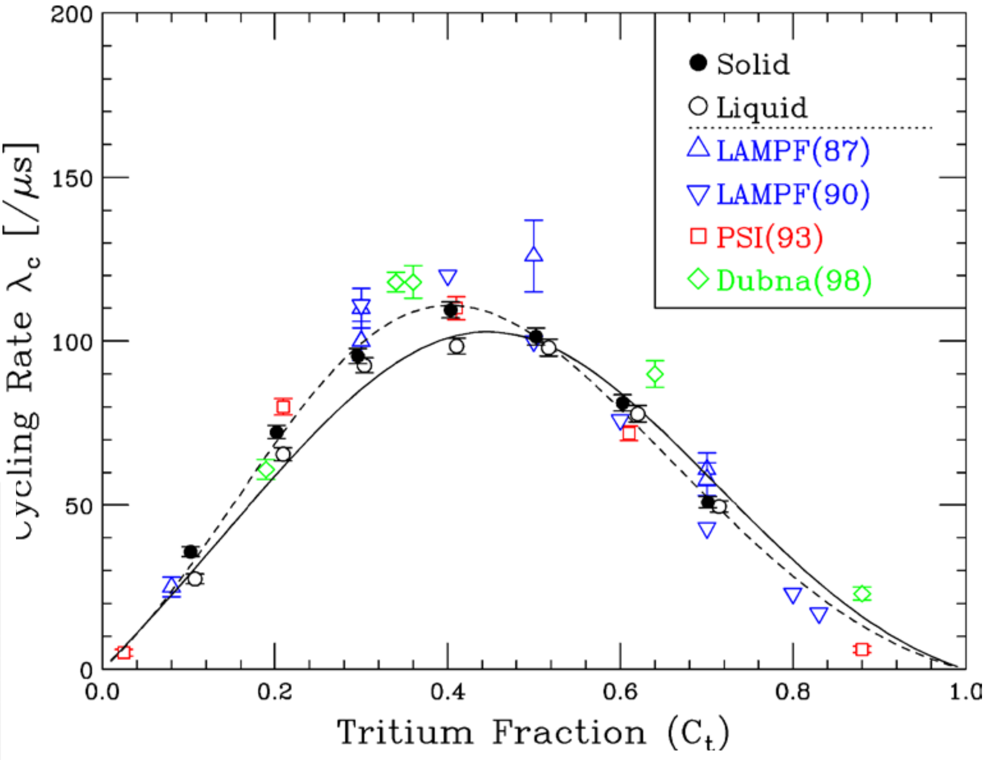
Ct=

MuCF measurement

Measurement of cycling rate and sticking probability at RIKEN-RAL





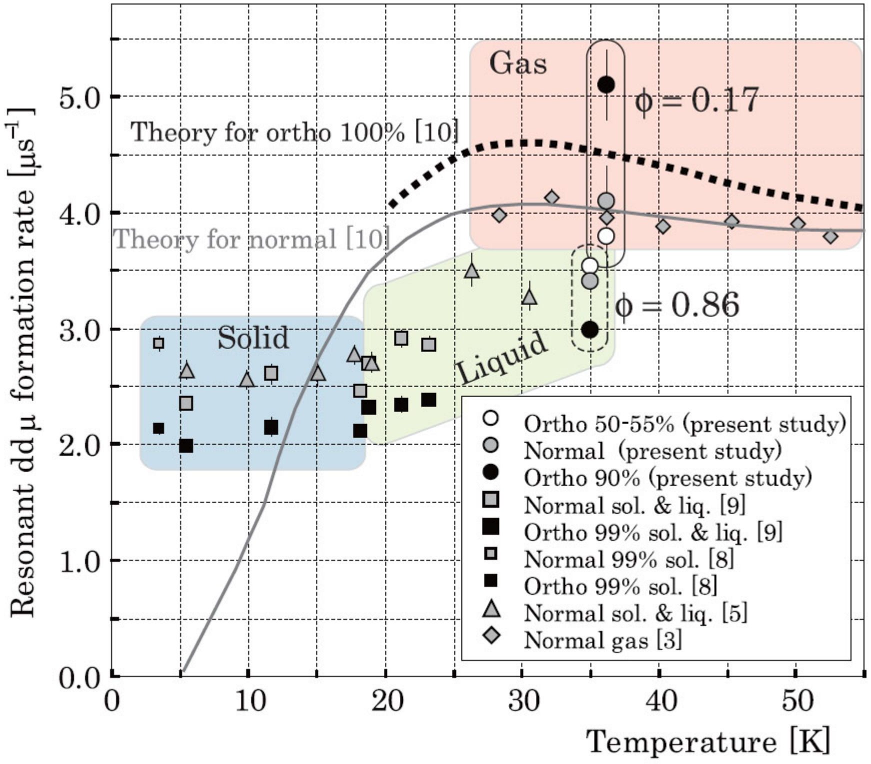


MuCF with ortho/para controlled target

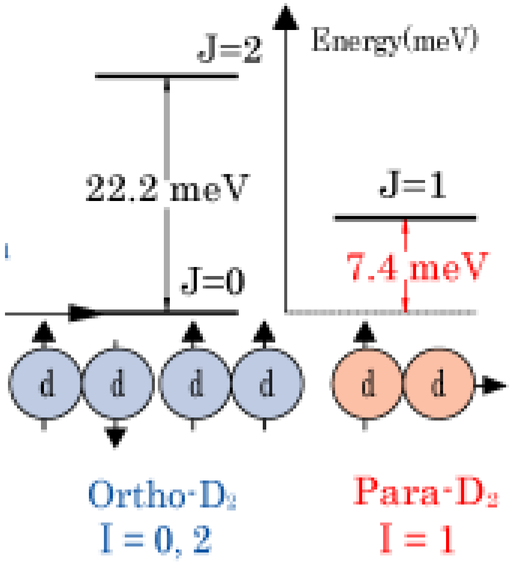
Enhancement of fusion yield with ortho/para control of D2 state

dd-fusion (TRIUMF S1129..)

Toyoda, Imao



dt-fusion (RAL)



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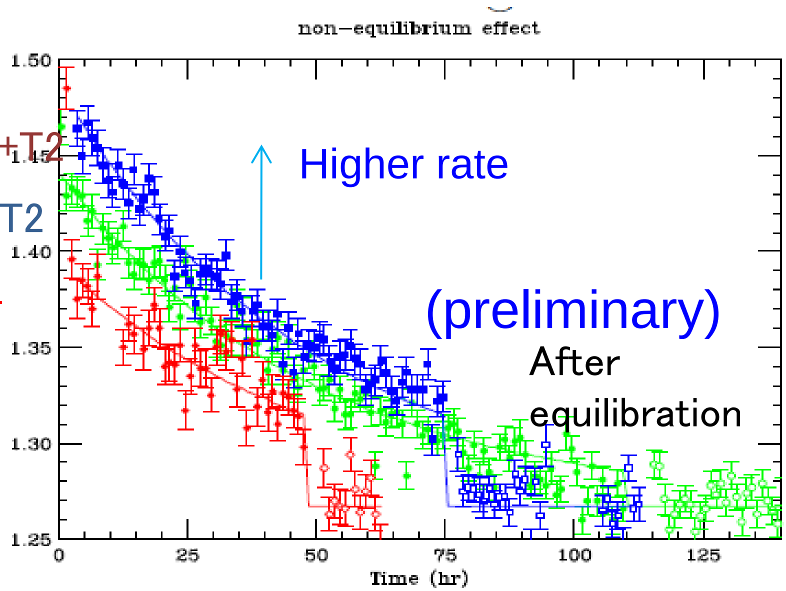
Enhancement of fusion yield with ortho/para control of D2 state

dt-fusion (RAL)



D2(Ortho)+T2

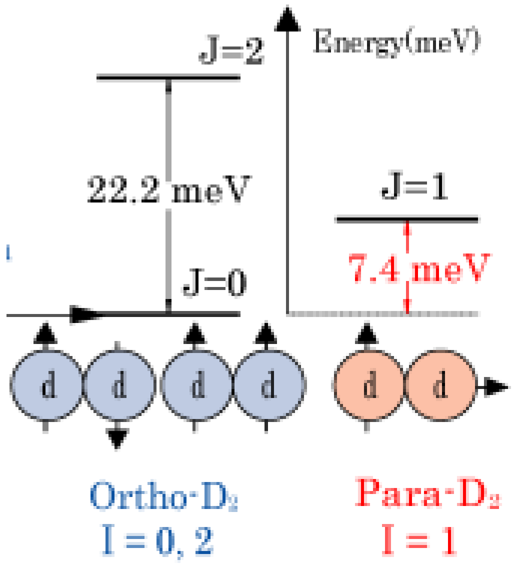
D2(Norm)+T2

D2(para-rich)+T2

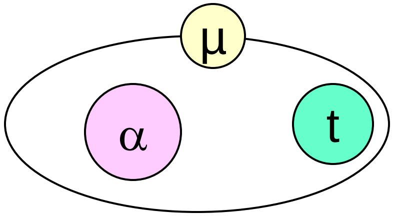
Higher rate

(preliminary)

After equilibration



Muon transfer to helium-3



(Another important loss process)

$(x^3He\mu)^*$ (X=p,d,t) molecule formation

$(x\mu) + He \rightarrow (xHe\mu)$

theoretically predicted [Popov, Kravtsov]

first observed in D_2+^{4}He [KEK 1987]

then also in D_2+^{3}He [KEK 1989]

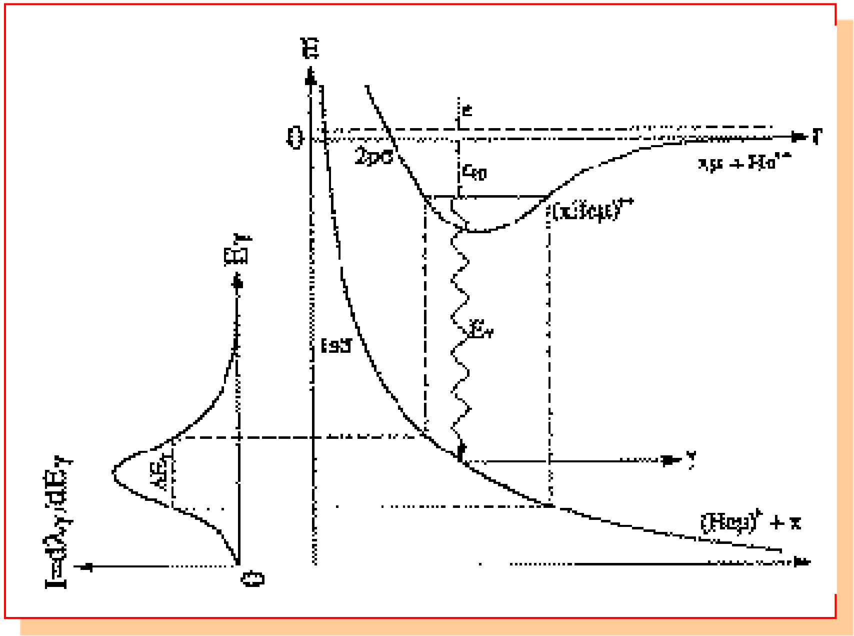
and T_2+^{3}He [RIKEN 1996]

formation rates

radiative & non-rad decay

[Kamimura, KEK/RIKEN]

fusion in $d^3He\mu$ (Dubnaa, PSI)



μCF in pure T_2

X-ray measurement with pulsed muon

1) radiative decay branch of $t^3He\mu$ etc

(competition with particle decay)

~20% $d^3He\mu$

~50% $d^4He\mu$

>90% $t^3He\mu$

2) α-sticking from ttμ fusion

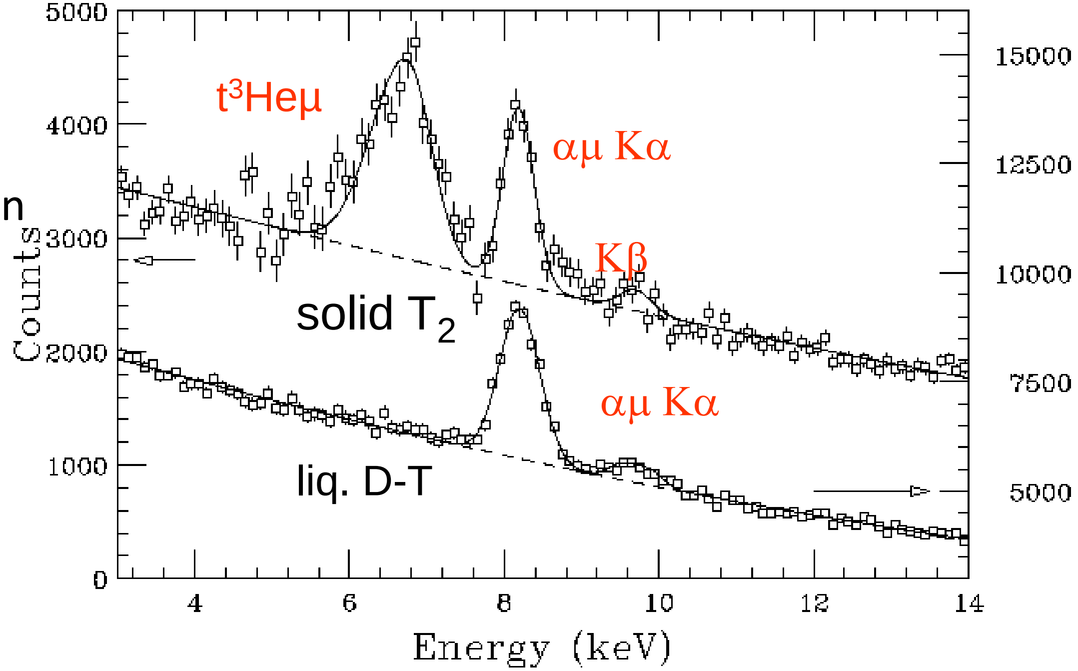
narrow peak = small αμ recoil

consistent with n-α correlation

detailed discussion of α-sticking

needs more statistics

and theoretical calc.



Muon transfer to helium (Solid, liquid effect)

Helium-3 from tritium decay

evaporates from liquid D-T

accumulates in solid D-T,

with anomaly around critical concentration C_{He}~120 ppm

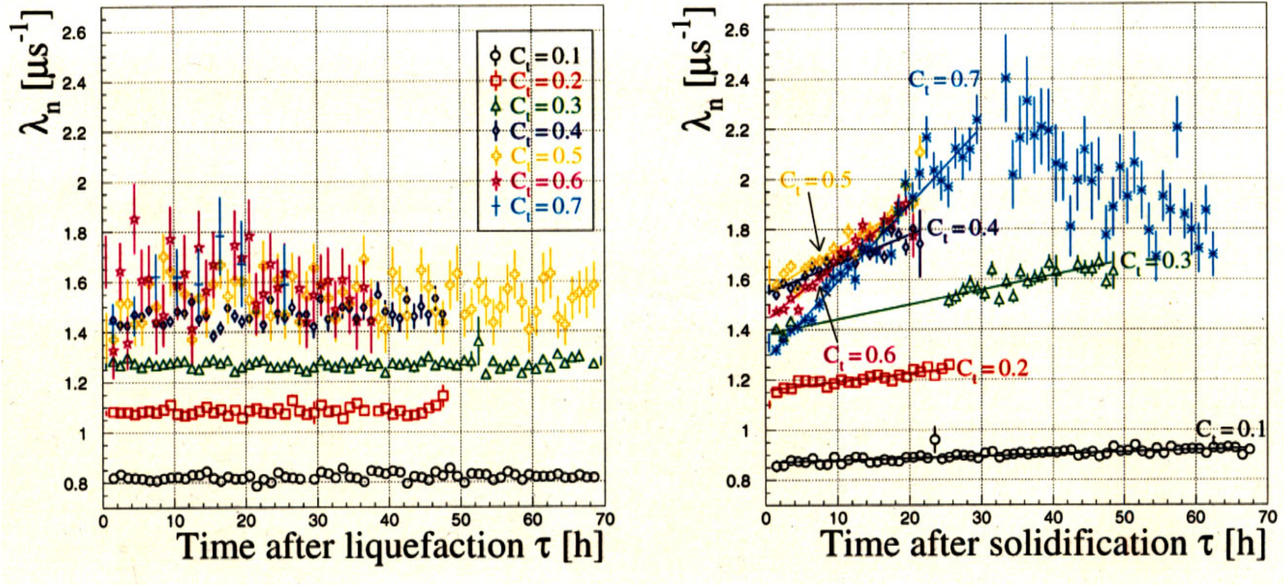
(reporoduceable in c_t=70%, pure T_2)

intrinsic property of helium in D-T

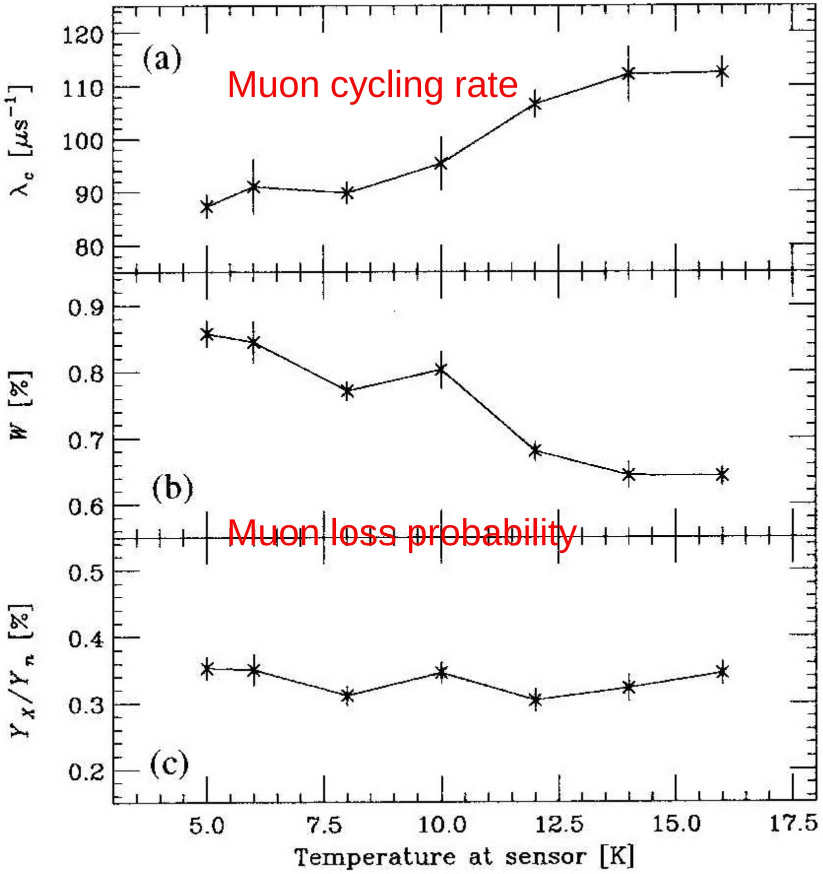
e.g. helium bubble formation

λ_n variation with time

Liquid vs Solid



Temperature dependence of d-t μCF cycling rate in D-T solid



Muon cycling rate

Muon loss probability

FIG. 2. Temperature dependence of (a) the muon cycling rate (λ_c), (b) the muon loss probability (W), and (c) the ratio of Y_X to Y_n at the tritium concentration of 0.4.

Kawamura et al.

D-T solid (40%)

Temperature: 5-17K

As temperature rises

λ_c : 20% increases

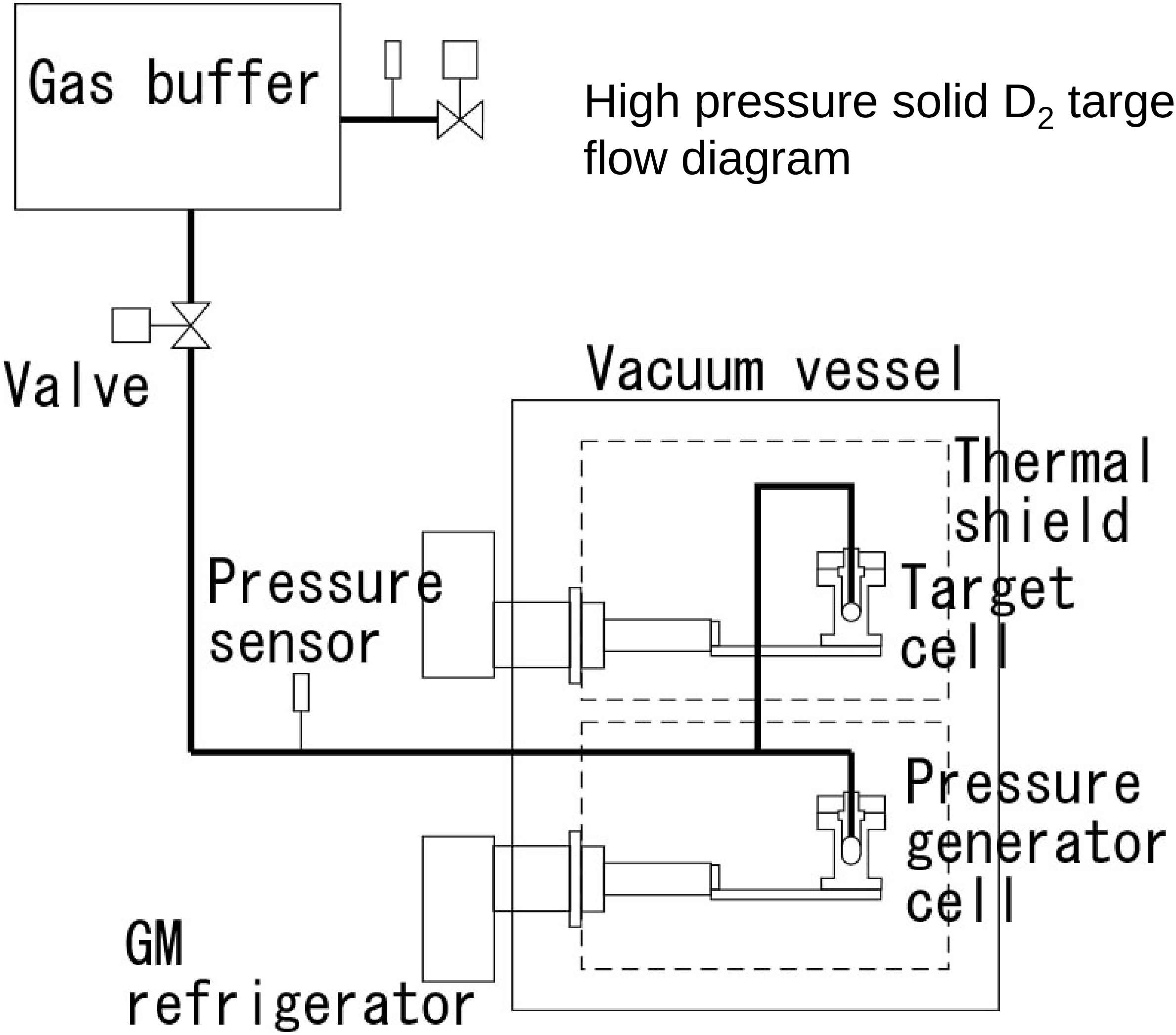
W: decreases

What happens in solid D-T at higher temperature ?

Highly pressurized solid D-T target

(1000 bar / 30K)

High pressure solid D_2 target system
（Muon catalyzed d−d fusion experiment）



High pressure solid D_2 target flow diagram

Stand alone system with D_2 buffer gas tank

Solid target vessel: 2.1cc

High pressure generator vessel: 4.8cc

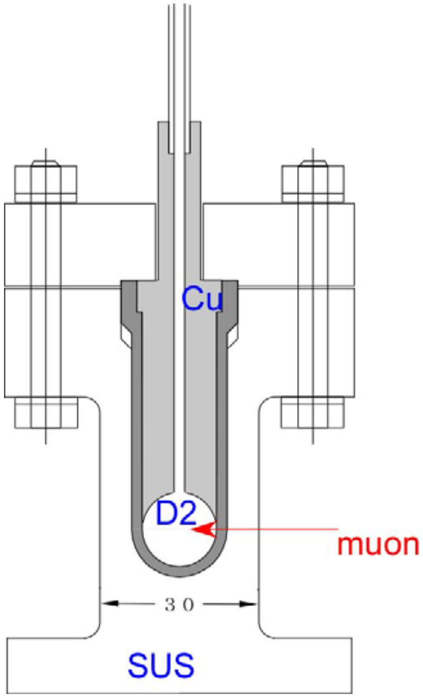
Dead volume: 4cc

Operation condition：
pressure 1,000 atm.
Temperature 30K

D_2gas volume：
about 10 liter

Closed cycle helium 4K cryostat（2 sets）
Only one control valve
Interlock system

High pressure solid D_2 target



Cross section of target vessel

Target inner vessel (cupper)

hydrogen permeation and brittleness

Pressure strength sustaining vessel

(stainless steel A286)

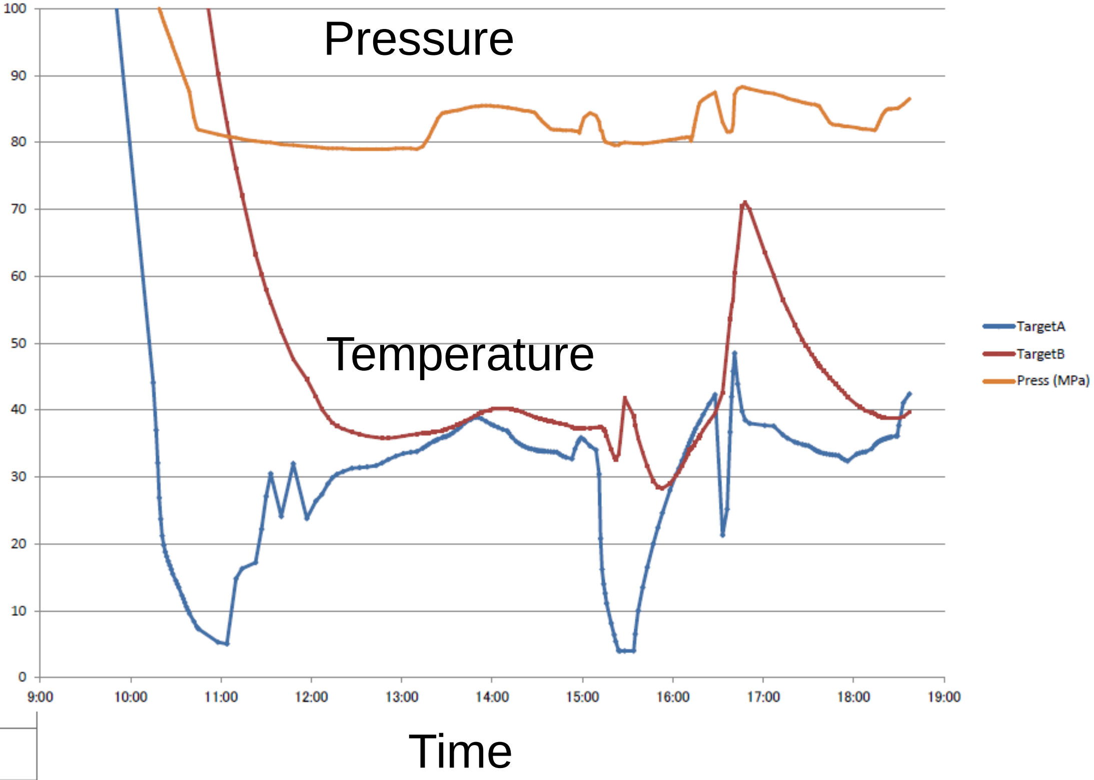
tested at 1500 bar

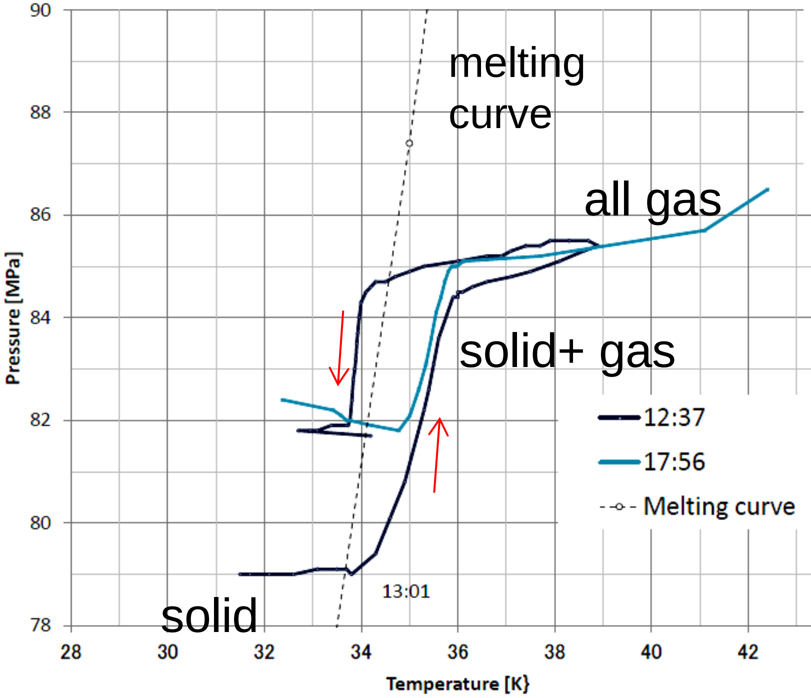
High Pressure MuCF Target

Test result (Nov 2012)

Matsuzaki, Ishida, Aikawa

Solid/Gas cycling





Confirmed formation of 33.5 K, 79 bar solid D2 target,

Present Status and Outstanding Problems

dtμ Molecular Formation

Resonant mechanism was basically established

$\lambda_{dt\mu}(\phi, T, E, Ct, \ldots)$ - very much dependent on condition

puzzles and surprises

(three-body, epithermal, non-equilibrium)

Muon-to-Alpha Sticking

Initial Sticking (0.9%) - hard to modify

Muon Reactivation - final sticking, Kβ/Kα ratio puzzle

Best conditions for μCF (several directions)

Solid D/T (high density) (Y_n~120 @PSI,RAL)

Non-equilibrium D/T (Y_n~124 @PSI tμ+D_2, ortho/para@RIKEN)

High temperature - high density (Y_n=150? @LAMPF,Dubna)

Epi-thermal tμ (TRIUMF)

Status/Plan at RIKEN-RAL

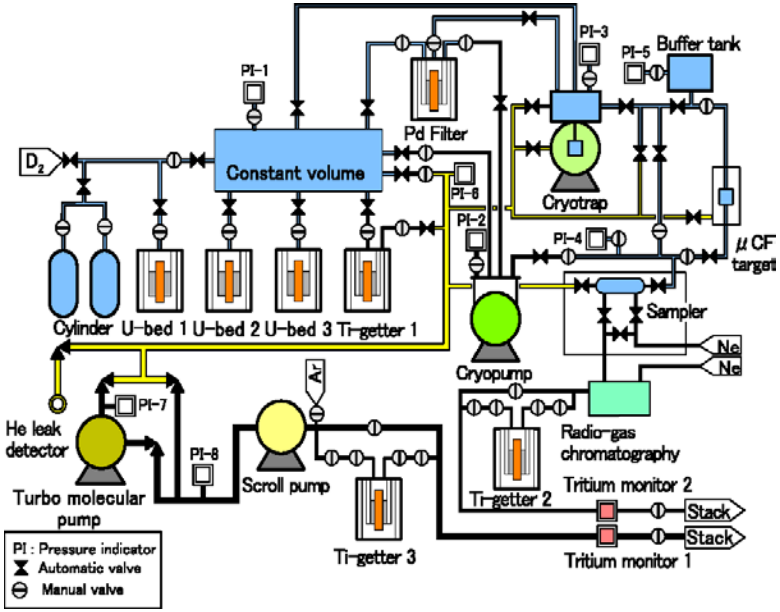
There has been no real beam measurement after 2006.

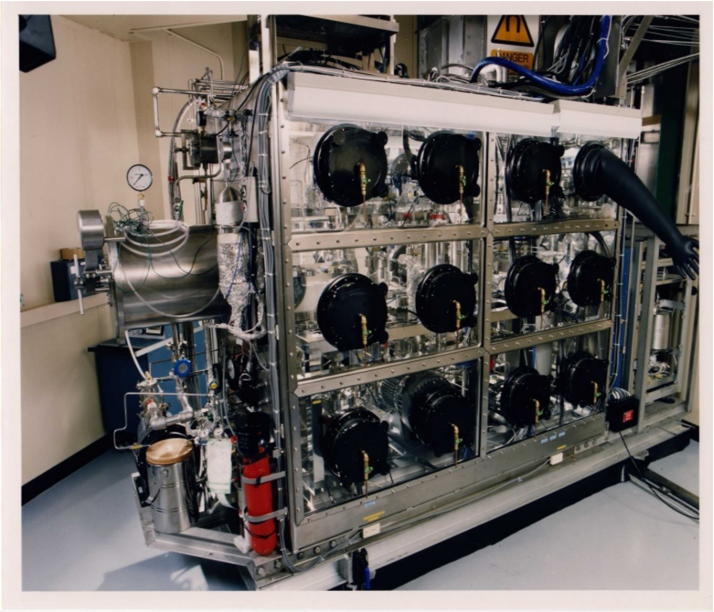
We needed a decision by 2018 => safe closure.

No further work is planned on μCF at RIKEN-RAL

The tritium gas is about to be transferred to outside user.

=> Good reuse of the system and saving money on disposal

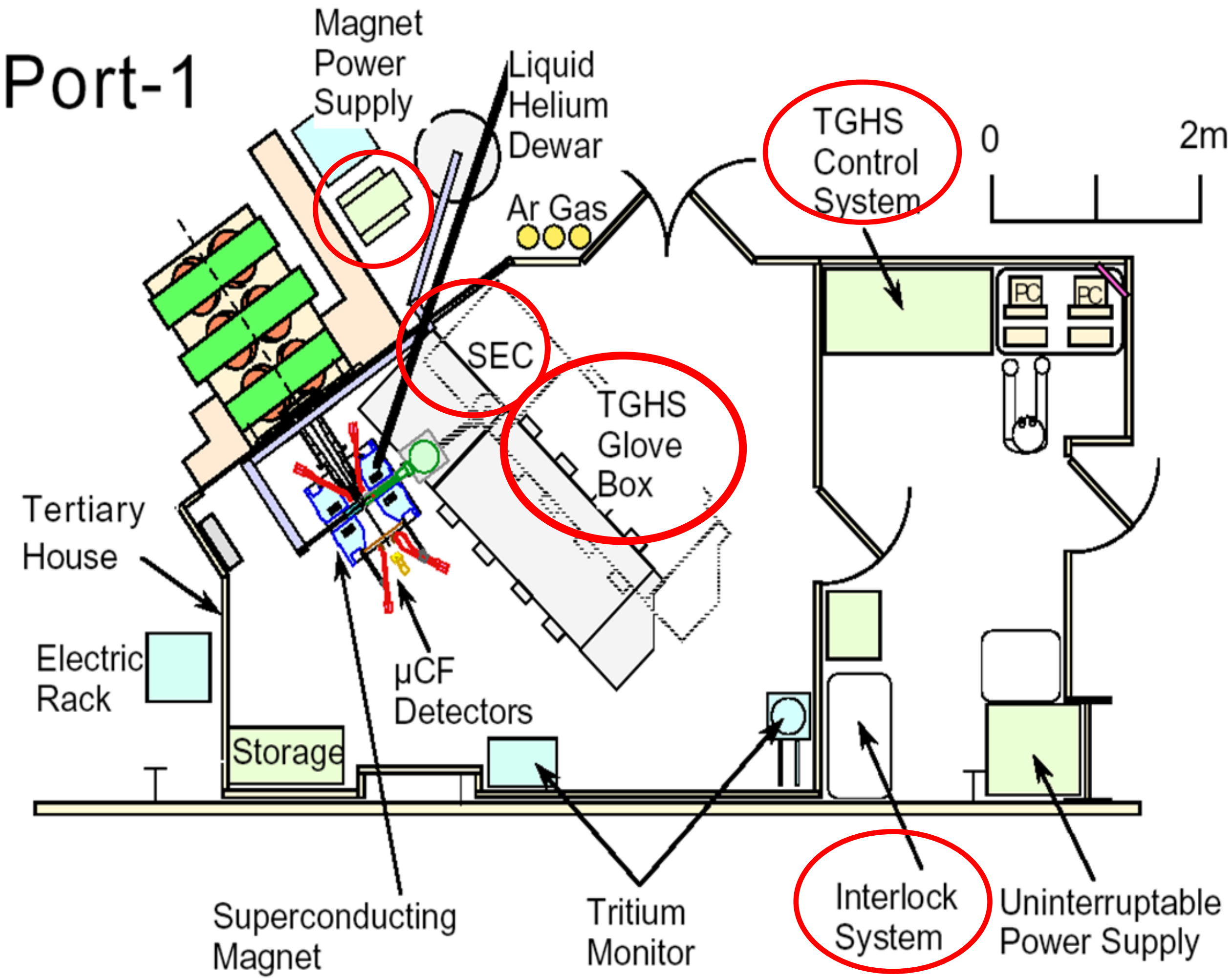




Decommissioning

mCF related facility will be removed.

Port-1 may be used for general purpose. (proton radius, for example)



Prospects

MuCF program at RIKEN-RAL has observed many interesting process.
We have to close it in a safe state.

The reduction of muon-to-alpha still seems difficult,
giving the limit on number of fusions.
If an efficient way of muon production is considered,
the balance could change the situation.